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This paper presents results from an effort to integrate the AFRL plasma modeling tool Coliseum with the SAIC/SEE, AFRL/VSB charging code Nascap-2k. Coliseum is used to compute the current collected by the test article at a fixed surface potential. Charging of the object is then computed by Nascap-2k and the new surface potential is exported to Coliseum. The process is iterated until surface potential reaches steady state. This approach is validated by modeling the floating potential of a conducting sphere as a function of electron temperature.

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Integration of the Coliseum plasma simulation tool with the charging code, Nascap-2k (PREPRINT)

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This paper presents results from an effort to integration the AFRL plasma modeling tool Coliseum with the SAIC/SEE, AFRL/VSB charging code Nascap-2k. Coliseum is used to compute the current collected by the test article at a fixed surface potential. Charging of the object is then computed by Nascap-2k and the new surface potential is exported to Coliseum. The process is iterated until surface potential reaches steady state. This approach is validated by modeling the floating potential of a conducting sphere as a function of electron temperature.

Nomenclature

j_e = electron current density
j_i = ion current density
i = current
ϕ = potential
T_i = ion temperature
T_e = electron temperature
k = Boltzmann constant
λ_D = Debye length
ϵ_0 = permittivity of free space
n = number density
e = elementary charge
j_0 = thermal flux current density
m_e = electron mass
m_i = ion mass

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I. Introduction

Any conducting object placed in contact with a plasma environment will collect electrical current. Due to the low mass of electrons, the electron current initially dominates the current collection, and the object will charge to a negative potential with respect to the ambient plasma. As the object potential becomes more negative, the electric field will repel electrons and attract ions, reducing the electron current and increasing the ion current. The final potential occurs when the ion current, j_i, at the surface is equal to the electron current, j_e.

The floating potential plays a significant role in the design of devices operating in a plasma environment. A negatively charged Faraday probe will attract ion current through the sheath, effectively increasing the probe area. In some cases, differential charging occuring between objects can result in a formation of a destructive arc.

The floating potential can be calculated analytically for objects with regular geometries, such as plates, cylinders or spheres. Modeling floating potential for more complicated configurations, however, requires the use of numerical tools. This work presents the initial effort to integrate two numerical tools: AFRL Coliseum, a plasma modeling tool to track particle flux to a surface, and SAIC/SEE, AFRL/VSB Nascap-2k, a differential surface charging code.

II. Coliseum Overview

Coliseum[1] is a 3D framework for modeling plasma dynamics and surface sputtering. It consists of three simulation modules: Ray, Aquila and Draco. Coliseum was developed under collaboration of the Air Force Research Laboratory with university and industry partners, including Virginia Tech, Massachusetts Institute of Technology, Colorado State University, University of Michigan and Advatech Pacific, Inc.

Draco[2] is an electrostatic particle-in-cell (ES-PIC) codes. It is a parallel code, which uses a Cartesian mesh to describe the volume. The mesh can be stretched along an arbitrary number of zones in each of the three axial directions. The surface boundary is specified using cut cells. Electrons can be treated either by using the hybrid approach based on the Boltzmann relationship, or as simulation particles. Draco also supports a real time erosion modeling, in which the surface is deformed according to the amount of eroded material.

The surface and/or volume meshes used by Coliseum are created by commercial off-the-shelf packages. The geometry of interest is first drawn in a CAD program, such as Solidworks. The solid object is subsequently imported to a mesh generator. Elements sharing common physical parameters, such as the native material or surface potential, are grouped into components. The resulting surface and/or volume mesh is exported for use with Coliseum. Coliseum supports a large number of commonly used FEM formats, such as Ansys, Abaqus, or Nastran.

The simulation is driven by a script file, which lists Coliseum commands and variable assignments. Besides loading the mesh files, a typical simulation will also load files specifying material and component properties. A material interaction file is also loaded to specify models and coefficients used to simulate particle collisions, surface impingement, and sputtering of native material. Particle injection models are specified by attaching sources to components.

Coliseum supports a large number of diagnostic probes, many of which approximate probes used in ground testing. Plasma properties, evaluated on the nodes of the volume mesh, and surface properties, centered on the nodes of the surface mesh can be exported at the end of the simulation. The data is saved in the Tecplot format to facilitate visualization and analysis of the results.

III. Nascap-2k Overview

Nascap-2k[3] is a three-dimensional spacecraft plasma environment interactions computer code that simulates a wide variety of plasma phenomena. These include spacecraft charging in geosynchronous, interplanetary, auroral, and low-Earth-orbit plasmas, volume potentials, particle trajectories, and resulting variations in plasma density.

Nascap-2k is targeted to spacecraft design engineers, spacecraft charging researchers, and aerospace engineering students. The graphical user interface is designed to help less experienced users easily solve moderately complex plasma interactions problems while allowing the expert user to tackle questions that

have not been previously contemplated.s

The core capabilities of Nascap-2k are the following:

1. Define spacecraft surfaces and geometry and the structure of the computational space surrounding the spacecraft

2. Solve for time-dependent potentials on spacecraft surfaces

3. Solve the electrostatic potential about the object, with flexible boundary conditions on the object and with space-charge computed either fully by particles, fully analytically, or in a hybrid manner

4. Generate and track electrons and ions, represented as macroparticles, including computing the resulting surface and volume, current and charge densities

5. View surface potentials, space potentials, particle trajectories, and time-dependent potentials and currents

The earliest and most common application of Nascap-2k is to study charging of spacecraft in geostationary orbit. Nascap-2k is designed to make this type of analysis particularly easy. Nascap-2k calculates surface potentials and electric fields using the Boundary Element Method (BEM), thus a simple charging calculation does not require a spatial grid. Nascap-2k contains a selection of predefined Maxwellian, double Maxwellian, and auroral plasma environments, which are readily modified to create custom environments. Other aspects of the environment include the magnetic field, the sun direction, and the sun intensity.

To solve for the electrostatic potential about the object, Nascap-2k uses a high-order finite element representation of the electrostatic potential that assures that electric fields are strictly continuous throughout space. The electrostatic potential solver uses a conjugate gradient technique to solve for the potentials and fields on the spacecraft surface and through the surrounding space. Several analytic and numerical space charge density models are available, including Laplacian, Linear, Non-linear, Frozen Ions, Full Trajectory Ions, Hybrid PIC (appropriate to the several microsecond timescale response to a negative pulse), and Full PIC.

Particle tracking is used to study sheath currents, to study detector response, to generate steady-state charge densities, or to generate space charge evolution for dynamic calculations. Nascap-2k generates macroparticles (each of which represents a collection of particles) either at a sheath boundary, the problem boundary, or throughout all space. Alternatively, particles can be initialized with a user-generated file. Particles are tracked for a specified amount of time, with the timestep automatically subdivided at each step of each particle to maintain accuracy. The current to each surface element of the spacecraft is recorded for further processing. The charge or current density created by the particles can be saved for use in solving for volume potentials.

IV.   Nascap-2k/Coliseum Interface

The integration presented in this paper did not require any modifications to the Nascap-2k code. The integration was performed with the version 3.1, which supports specifying of surface current through user built dynamically linked library (DLL). The DLL built for this integration accomplished two primary tasks:

- Provide Coliseum surface current to Nascap-2k

- Output computed surface potential in a Coliseum-compatible format

Nascap-2k requires the DLL to export two functions: *setEnvironmentParams* and *getCustomCurrent*. The first function is called at the start of every charging cycle. The primary role of this function is to provide the DLL with properties specifying the ambinet plasma environment. The second subroutine is called at every time step for every surface element. This function provides Nascap-2k with the value of the current to the element, i, as well as its derivative in respect to potential, $\partial i/\partial \phi$.

The DLL obtains the surface current information by parsing a file output by Coliseum's SURFACE_SAVE command. The standard output format, Tecplot, is supported. The interface file must contain potential ("PHI") and surface current density ("CURRENT") among the saved node properties. The parsed data is stored in an internal data structure. A screenshot of Nascap-2k with the calculated potential map is shown in Figure 1.
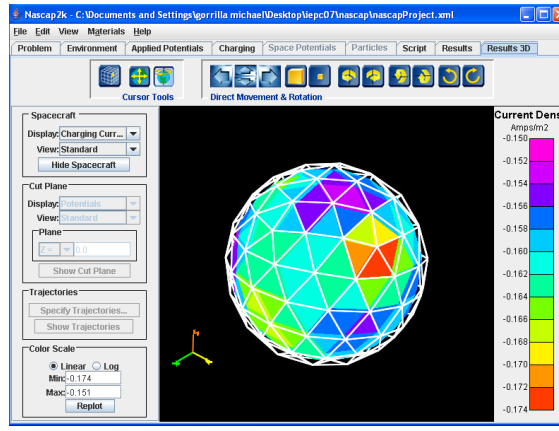
Figure 1. Nascap window with calculated surface potential.

The Coliseum node-centered current density is averaged onto the element centroid, before being returned by the *getCustomCurrent* function. At the end of every charging time step, the DLL outputs a Tecplot file containing the updated surface potential, scattered from the element centroid onto the surface nodes.

V.   Validation Study

A.   Simulation Setup

The Coliseum/Nascap-2k integrated approach was validated by modeling the charging of a conducting sphere located in ambient plasma. Prokopenko and Lafrombaise[4] developed an analytical solution for this problem in the *thick sheath* limit. This condition applies when the thickness of the sheath is is significantly greater than the characteristic dimension of the object. In this work, this condition was maintained by selecting sphere radius smaller than the sheath in any of the tested configurations.

The sphere radius was set to 1.5cm. The density of the ambient plasma was $3 \times 10^{-3} \text{m}^{-3}$. The ion temperature was fixed at $T_i = 0.1\text{eV}$, while the electron temperature was varied from $kT_e = 1\text{eV}$ to $kT_e = 100\text{eV}$. The Debye length, given by

$$\lambda_D = \sqrt{\frac{\varepsilon_0 k T_e}{n e^2}} \tag{1}$$

hence varied from $4.29 \times 10^{-3}\text{m}$ at $kT_e = 1\text{eV}$ to $4.29 \times 10^{-2}\text{m}$ at $kT_e = 100\text{eV}$. The sheath thickness, which for a Maxwellian plasma can approximated by

$S \sim 10\lambda_D$, can be seen to be greater than 1.5cm in the range of tested electron temperatures. The Coliseum domain decomposition is shown in Figure 2.

B.   Current Collection

Since charging scales with collected current, it was necessary to validate the current collection in Coliseum before proceeding with charging simulations in Nascap-2k. The electron and ion current densities collected by a charged sphere with potential negative to the ambient plasma are given[4] by

$$j_i = j_0 \left(1 - q\phi_s/kT_i\right) \tag{2}$$

$$j_e = j_0 \exp\left(-q\phi_s/kT_e\right) \tag{3}$$

where $j_0 = qn_0\sqrt{kT/(2\pi m)}$ is the current due to thermal flux in the indisturbed plasma. Current collection was tested by varying the potential applied to the sphere for three values of electron temperature, 1eV, 10eV and 100eV. The potential was varied from $\phi_s = 0\text{V}$ to $\phi_s > \phi_f$. As can be seen in figure 3, the simulation current agrees well with the analytical profile.
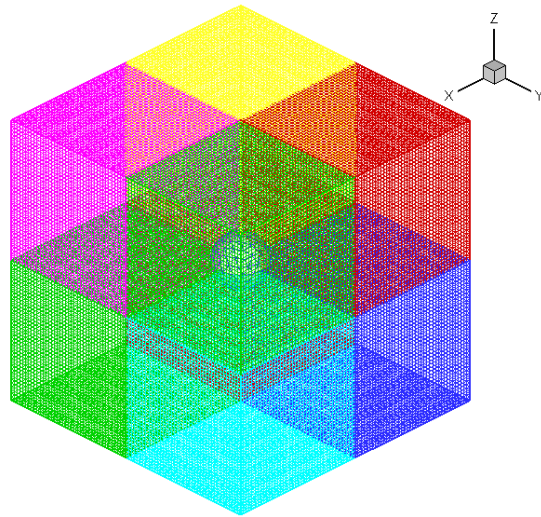
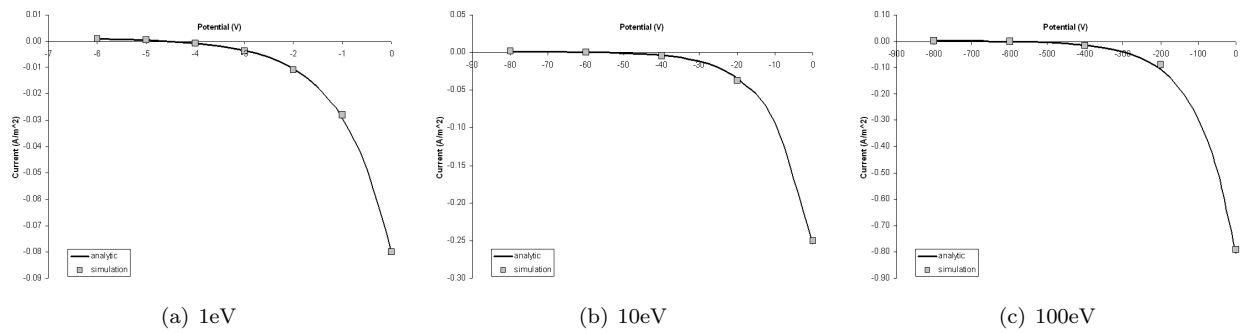**Figure 2. Domain decomposition of Coliseum simulation.**

(a) 1eV   (b) 10eV   (c) 100eV

Figure 3. Current collection by a sphere of three set potentials.

C. Calculation of Floating Potential

Next, the floating potential was calculated using the integrated Nascap-2k approach. An analytical expression for the floating potential can be obtained from Eq. 3 by setting $j_e = j_i$. The resulting equation,

$$\phi_s = -\frac{kT_e}{e} \ln \left[\sqrt{\frac{T_i}{T_e} \frac{m_i}{m_e}} \left(1 - e\phi_s/kT_i\right) \right] \tag{4}$$

can then be solved using numerical methods to obtain relationship shown in Figure 4.
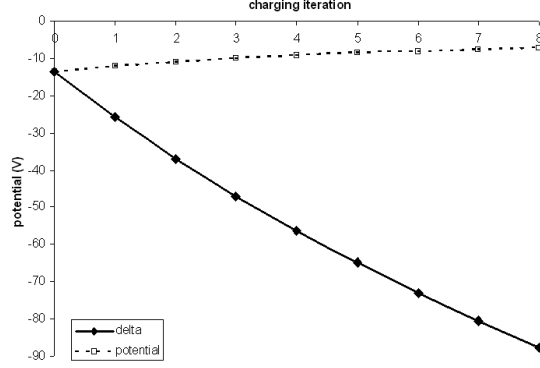

Figure 4. Progression of surface charge over time.

Floating potential was calculated for $kT_e = 1\text{eV}$, 10eV and 100eV. Figure 5 shows the current collected by Coliseum and the corresponding potential as computed by Nascap-2k. Since the sphere is a conductor, the surface potential reaches a uniform value, despite small variations in surface current. Figure 4 shows the surface potential and collected current as a function of simulation iteration. Each point corresponds to an individual Coliseum simulations executed until steady state. As expected, both surface potential and collected current decrease, until the floating potential is reached where $j = 0$. The floating potential, graphed versus kT_e, can be seen in in Figure 5. Comparison with the analytical model of Eq. 4 indicates a very good agreement.
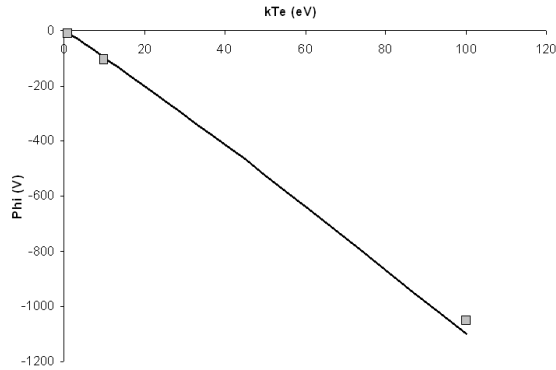

Figure 5. Calculated floating potential of a sphere versus plasma temperature.

VI. Conclusion and Future Work

Two complimentary simulation codes, Coliseum and Nascap-2k, have been integrated and used together for the purpose of modeling surface charging due to plasma environments. This work represents a proof of concept of the integration by illustrating a simple test case. A charged sphere was placed in an ambient plasma and the current to the sphere was measured using Coliseum. The current to the sphere was then

loaded into Nascap-2k which performed a charging calculation. The resulting potential was then imported back into Coliseum and the process was repeated until a steady state was reached. This paper represents a simple proof of concept. More advanced studies will be performed that utilize the advanced plume modeling of Coliseum and the differential charging capabilities of Nascap-2k.

Currently, the integration between Coliseum and Nascap-2k is performed via a manual exchange of input/output files. In the future this process will be automated, possibly through a direct link between the programs. This will allow simulations to reach a steady state without user interaction.

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